Signatures of black hole spin in galaxy evolution

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ABSTRACT

We explore the connection between black hole spin and AGN power by addressing the consequences underlying the assumption in the recent literature that the gap region between accretion disks and black holes is fundamental in producing strong, spin-dependent, horizon-threading magnetic fields. Under the additional assumption that jets and outflows in AGN are produced by the Blandford-Znajek and Blandford-Payne mechanisms, we show that maximum jet/outflow power is achieved for accretion onto black holes having highly retrograde spin parameter, an energetically excited yet unstable gravitomagnetic configuration.

Subject headings: galaxy: evolution — black hole physics

1. Introduction

The paradigm that has emerged for the production of outflows from active galactic nuclei (AGN) involves the presence of large scale electromagnetic fields which are instrumental in their formation, acceleration and collimation, many gravitational radii from the central supermassive black hole (Nakamura et al, 2008; Meier et al, 2001; Blandford, 1976; Lovelace, 1976). Two models have taken center stage. Blandford & Payne (1982; henceforth BP) and extensions of this model (Li et al, 1992 and Vlahakis & Konigl, 2003) describe a centrifugally driven outflow of gas originating in a cold accretion disk as a solution to ideal MHD within the context of self-similarity. If the angle between the poloidal component of the magnetic field and the disk surface is less than 60 degrees, mass-loading of the magnetic field lines occurs, leading to an inbalance between inward gravitational and outward centrifugal forces, with gravity being overwhelmed. Unlike the BP mechanism which taps into the gravitational potential energy of the accretion flow, the Blandford-Znajek (1977; henceforth BZ) mechanism produces relativistic jets from large scale magnetic fields threading the rotating event horizon by extraction of black hole rotational energy. The flux-trapping model (Reynolds et al, 2006) is an attempt to understand ways in which black hole accretion flows can overcome their diffusive character (see also Bisnovatyi-Kogan & Lovelace, 2007 and Rothstein & Lovelace, 2008) to produce strong magnetic field on the black hole (see Bisnovatyi-Kogan & Ruzmaikin, 1976, for earliest attempt to study the accretion of large-scale ordered magnetic field on black hole) indicating that if the flux-trapping behavior of the gap/plunge region is valid, the BZ mechanism produces greatest power for black hole spin of $a \approx -1$ (Garofalo, 2009). Here we show that the same is true for the BP mechanism. This means that although the spin dependence of BZ and BP power is different overall, they both peak for near maximal retrograde black hole spin. We motivate the idea that 'ordinary' astrophysical processes will tend to shift near maximal retrograde black hole accretion systems toward more prograde

spins (i.e. accretion and/or spin energy extraction). Once formed (e.g. in galaxy mergers), such systems will evolve toward a state of lower power output, which implies that the population density of near maximal retrograde black hole accretion systems that produce outflows and jets, is larger at the redshift of formation of the highly retrograde accretion systems and naturally tends to drop, so that the cosmological evolution of black hole spin is in the direction of prograde spins. In section 2 we describe the basic geometry of the flux-trapping model. In section 3 we discuss its implications for the BP power and those of assuming that outflows and jets in AGN are all due to either BZ, BP, or a combination of both mechanisms (Meier, 1999). In section 4 we conclude.

2. The model

The basic feature of our model is illustrated in Figure 1 where magnetic field lines threading the black hole are separated from those threading the disk by a gap region (or plunge region). The absence of magnetic field threading the gap region is the fundamental assumption of the flux-trapping model (Reynolds, et al, 2006). This assumption has implications for both the BZ and BP effects of which the former are illustrated in Figure 2, originating from the numerical solution to the MHD equations in a Kerr metric (Garofalo, 2009). We emphasize the fact that maximum BZ power is produced for highly retrograde black hole spin, and extend the flux-trapping model to outflows of the BP type, with the basic point to motivate the existence of a spin dependence in BP power that is also maximized at high retrograde black hole spin values. The model is further described below.

1. Our accretion disk is described by a Novikov & Thorne (1974) disk truncated at the marginally stable orbit, inwards of which is the gap region.

2. In the magnetosphere (the region outside of the black hole and accretion disk) we

assume that the plasma density is negligible and hence that the magnetic field is force free.

3. We assume that no magnetic flux threads the gap or plunge region of the accretion disk. Any magnetic flux that is advected inwards across the radius of marginal stability is immediately added to the flux bundle threading the black hole.

4. Far away from the black hole and at poloidal angles above the accretion disk, we assume the large-scale field is uniform.
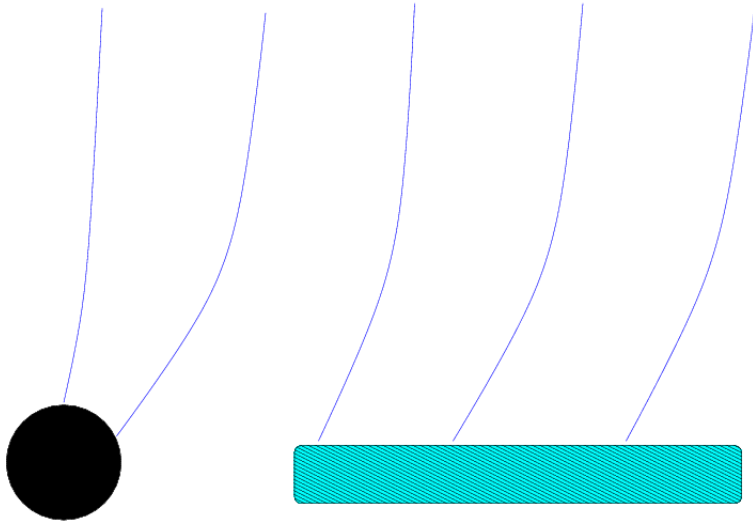

Fig. 1.— A black hole accretion disk (with the no-flux gap region boundary condition) threaded by large scale magnetic field that is parallel to the black hole spin axis far from the accretion disk.
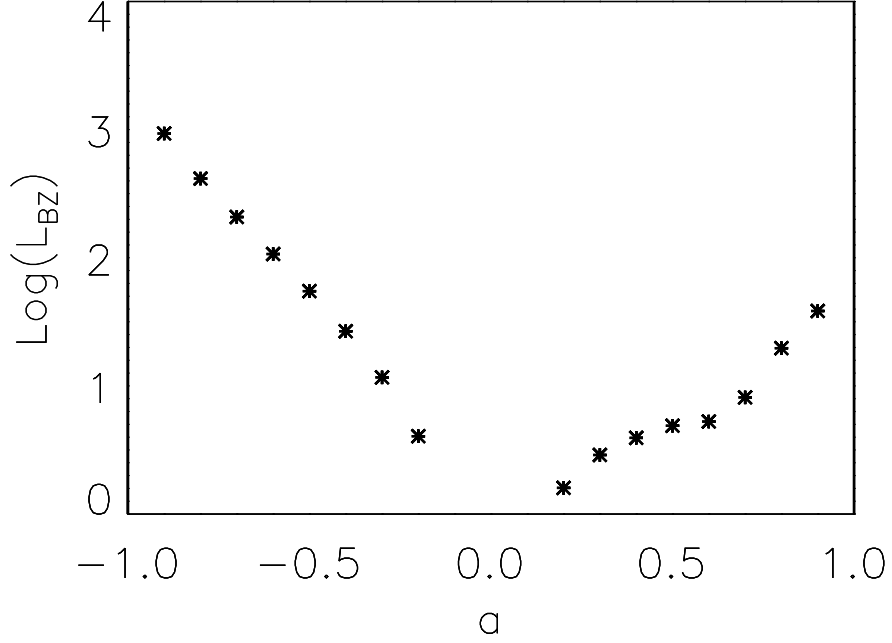
Fig. 2.— Blandford-Znajek power vs. spin according to flux-trapping.

3. BP outflows and the cosmological evolution of black hole spin in the flux-trapping model

In this section the focus is on the geometry of the magnetic field as in figure 1 and the changes that occur as the spin of the black hole varies. Because BP outflows depend on the angle between the magnetic field and the accretion disk surface, the emphasis is on how this angle changes with spin. Despite highlighting MHD force balance in the force-free magnetosphere, the discussion remains qualitative, limiting the study to identifying the spin value for which BP power is maximized. Magnetic forces between the flux bundle on the hole and that threading the disk compete at latitudes above the equatorial plane where the no-flux boundary condition is imposed (see arrows in Fig. 3). Whereas magnetic pressure/tension of magnetic field lines threading the disk tend to push the hole-threading

flux bundle onto the horizon, the latter reacts back on the disk-threading magnetic field to limit additional magnetic field advection onto the black hole. The bend in the magnetic field threading the disk stems from the fact that while the radial inflow of the accreting gas attempts to drag the large scale magnetic field toward the black hole, the aformentioned magnetic forces from the flux bundle already threading the black hole, push the magnetic field lines threading the disk outward. The greater the magnetic flux bundle on the black hole, the more effective its ability to halt additional advection from the disk, and the greater the bend inflicted on the magnetic field lines threading the disk. As Fig. 3 illustrates, the magnitude of the black hole-threading flux bundle depends on the ability of the gap region to drag magnetic field inward. For high prograde-spinning black holes, the marginally stable circular orbit is close to the black hole horizon in both coordinate and proper distance which makes the gap region ineffective at dragging large magnetic flux to the horizon. In the low-spin or retrograde case, instead, the inner edge of the accretion disk at the marginally stable circular orbit is much further out so the proper distance to the horizon from the disk inner edge is larger. This means that slowly spinning or retrograde black holes acquire magnetic flux via the gap region further out in radial position compared to their high-spin counterparts, resulting in a larger magnetic flux bundle on the horizon. As BP point out, if the magnetic field lines and the disk surface meet at an angle that is 60 degrees or less, a centrifugally-driven MHD wind is possible. With respect to their high-spin counterparts, then, low-spin or retrograde systems are more likely to exhibit bent magnetic field line configurations which makes them comparatively better candidates for BP outflows. This behavior is seen in the steady-state magnetic field configurations of the numerical solution (figures 4 and 5). We choose a representative set of disk parameters such as disk thickness, accretion rate, Prandtl number etc., and illustrate the geometry of the numerical solution. We find that the magnetic field lines threading the retrograde system are bent well out into the disk. The high prograde spin system, on the other hand, displays bent magnetic

flux contours only in the innermost region of the accretion disk and even there the bend is small. In short, as the spin of the black hole decreases from high prograde toward high retrograde values, the magnetic field lines bend progressively more toward the disk surface. If we associate this feature with greater BP outflow power, the arguments suggest that the spin dependence of BP power in the flux trapping model increases progressively from high prograde spins to high retrograde spins. Therefore, like the BZ power, the BP power is maximized for $a \approx -1$.

Assuming that the BZ and BP mechanisms are the dominant path chosen by nature to produce outflows and jets in AGN within the context of the flux-trapping model, leads to the conclusion that retrograde black hole accretion systems threaded by large-scale magnetic fields, tend toward prograde black hole spin systems unless some external factors beyond accretion and black hole rotational energy extraction occur. Accretion in retrograde systems, in fact, adds angular momentum to the hole in the prograde sense. In addition, the BZ power is largest for high retrograde spins which means that greatest spin energy extraction occurs to reduce the absolute value of the hole's angular momentum. The BP mechanism, on the other hand, does not directly affect the black hole spin. Clearly, accretion and spin-energy extraction via BZ both operate to increase the spin away from $a \approx -1$. How fast it moves away from $a \approx -1$ and whether it crosses $a = 0$ depends on the rate at which angular momentum is extracted by the BZ mechanism as well as on the rate at which angular momentum is supplied by accretion. The one thing that is clear, though, is that the most energetic outflows and jets produced in $a \approx -1$ systems are not stable, so the spin must change. Thus, if flux-trapping via the plunge region occurs in nature, the most powerful AGN evolve to lower energies as their black hole spins become more prograde.
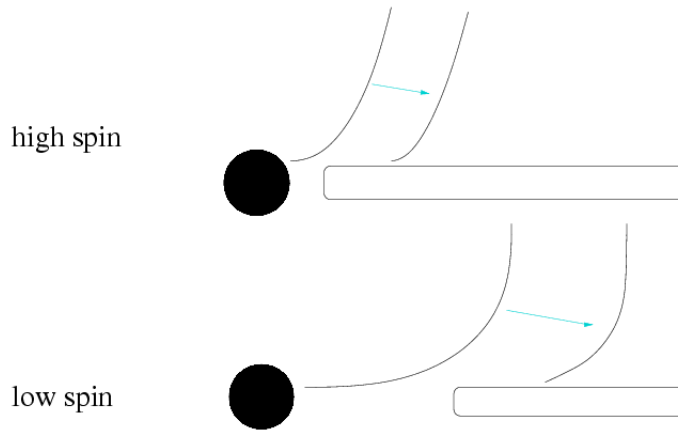
Fig. 3.— The difference in the geometry between a high spinning black hole accretion disk (top) and a low spinning or retrograde black hole accretion disk (bottom). In the high-spin case the gap region is small and the black hole acquires little magnetic flux from the dragging of magnetic field through it. The resulting weak flux bundle on the hole has little effect on the magnetic field threading the disk whose geometry remains thus mostly vertical. In the low-spin or retrograde case, instead, the gap region is large and it drags a strong flux bundle onto the horizon. The strength of this flux bundle compared to that in the high spin case is such that it is comparatively more effective in deforming the disk-threading magnetic flux lines which bend.

4.   Conclusions

This work extends the relativistic flux-trapping model to include outflows of both the BZ and BP type in an effort to constrain the cosmological evolution of black hole spin (e.g. Brenneman, 2009) and its possible connection to powerful outflows such as those in radio loud galaxies (Evans et al., 2009, in press). Our current picture of the interaction between
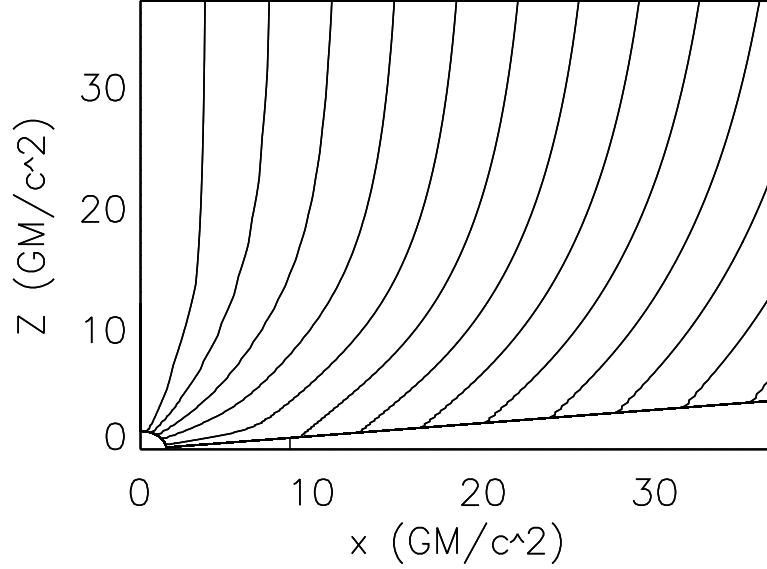
Fig. 4.— Magnetic configuration for a -0.90 retrograde spinning black hole and its accretion disk. Notice the large bend at 30 gravitational radii compared to the high prograde figure.

black holes in AGN and the host galaxy, suggests a coherent two-way conversation in which the host galaxy speaks to the black hole about the galaxy via accretion by funneling matter toward the black hole, and the black hole speaks to the galaxy about the black hole via outflows that leave signatures of its mass (Kormendy & Richstone, 1995; Magorrian et al. 1998; Marconi & Hunt, 2003; Gebhardt et al. 2000; Ferrarese & Merritt, 2000; Tremaine et al, 2002). If the behavior of the gap region is as fundamental as assumed here, this two-way conversation includes more, one in which the more subtle features of the highly non-Newtonian aspects of space and time that dominate the region close to the center of galaxies are also revealed. In fact, the scenario that emerges is one in which the spin parameter of the central supermassive black hole is not simply revealed in the generated outflow, but is an active participant in the dynamics of the latter, to the extent that it sets the scale for the magnitude of the outflow power. The overall conclusion of the assumption
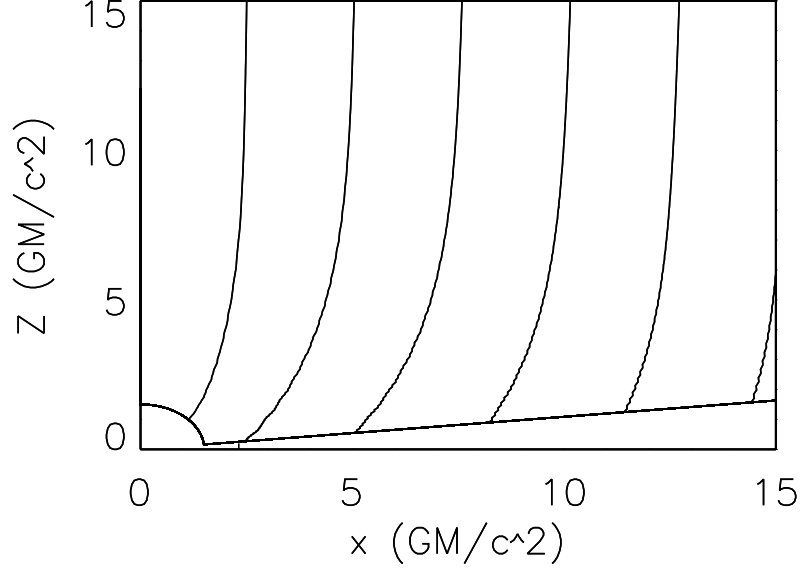
Fig. 5.— Magnetic configuration for a 0.90 prograde spinning black hole and its accretion disk. Notice how the flux lines in the disk are only slightly bent at 15 gravitational radii unlike the high retrograde case where they are considerably bent at that location.

that BP and BZ operate within the context of flux-trapping is that galaxy evolution is tightly coupled to black hole spin.

5. acknowledgments

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